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Accretion does not drive the turbulence in galactic discs

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ABSTRACT

Rapid accretion of cold intergalactic gas plays a crucial role in getting gas into galaxies. It has been suggested that this gas accretion proceeds along narrow streams that might also directly drive the turbulence in galactic gas, dynamical disturbances and bulge formation. In cosmological simulations, however, it is impossible to isolate and hence disentangle the effect of cold stream accretion from internal instabilities and mergers. Moreover, in most current cosmological simulations, the phase structure and turbulence in the interstellar medium (ISM) arising from stellar feedback are treated in an approximate (subgrid) manner, so that the feedback cannot generate turbulence in the ISM. In this paper we therefore test the effects of cold streams in extremely high-resolution simulations of otherwise isolated galaxy discs using detailed models for star formation and stellar feedback; we then include or exclude mock cold flows falling on to the galaxies, with mass accretion rates, velocities and flow geometry set to maximize their effect on the gaseous disc. We find (1) turbulent velocity dispersions in gas discs are identical with or without the presence of the cold flow; the energy injected by the flow is efficiently dissipated where it meets the disc. (2) In runs without stellar feedback, the presence of a cold flow has essentially no effect on runaway fragmentation (local collapse), resulting in star formation rates (SFRs) that are an order-of-magnitude too large. (3) Model discs in runs with both explicit feedback and cold flows have higher SFRs, but only insofar as they have more gas. (4) Because the flows are extended, relative to the size of the disc, they do not trigger strong resonant responses and so induce weak gross morphological perturbation (bulge formation via instabilities/fragmentation is not accelerated). (5) However, flows can thicken the disc by direct contribution of out-of-plane or misaligned star-forming streams/filaments. We conclude that while inflows are critical over cosmological time-scales to determine the supply and angular momentum of gas discs, they have weak *instantaneous* dynamical effects on galaxies.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – galaxies: star formation – cosmology: theory.

1 INTRODUCTION

Since some of the earliest models of galaxy formation in a cosmological setting, it has been known that in low-mass haloes ($\lesssim 10^{11-12}\,\mathrm{M}_{\odot}$), the gas cooling time is shorter than the dynamical time even if gas is shock heated to virial temperature before accretion. In this case shock heating during virialization will not provide sufficient pressure support for the infalling gas and gas could reach galaxies in near free-fall [Binney 1977; Rees & Ostriker 1977; Silk 1977; White & Rees 1978; for a more detailed spherical shock stability analysis with a modern Λ cold dark matter (ΛCDM) cosmology, see Birnboim & Dekel 2003]. In recent years, numerical hydrodynamic simulations have considerably improved our understanding of this regime which is part of a more general process termed 'cold accretion' or 'cold flows'. Kereš et al. (2005) argued that in lower mass systems, gas can reach galaxies in free-falling filaments which are cold ($\sim 10^4$–10^5 K) by virtue of their large densities preventing an accretion shock; at high redshifts ($z \gtrsim 2$), such streams may even penetrate more massive haloes (where the spherically averaged $t_{\rm cool} \gg t_{\rm dyn}$) because of the highly non-spherical nature of accretion. In this early work the gas accreted by galaxies in massive haloes was shown to largely come from the

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'hot mode accretion', i.e. most of the infalling filamentary gas heats before reaching galaxies. A large body of subsequent theoretical work has developed on this topic (see e.g. Dekel & Birnboim 2006; Ocvirk, Pichon & Teyssier 2008; Brooks et al. 2009; Dekel et al. 2009b; Kereš et al. 2009; Oppenheimer et al. 2010, and references therein). At the same time, tantalizing observational evidence for the existence of infalling cool gas is emerging (Ribaudo et al. 2011; Kacprzak et al. 2012), although systematic detection of large gas infall rates in high-redshift haloes is still lacking (Sancisi et al. 2008; Steidel et al. 2010).

The exact nature of the accretion process in massive ($\sim 10^{12}\,\mathrm{M}_{\odot}$) haloes is still a subject of a debate, owing to the sensitivity of predictions to details of the treatment of gas and 'feedback' physics. All simulations agree that most of the gas in massive haloes heats to high temperatures. The debate is mostly about the detailed nature of the infalling gas in the vicinity of galaxies. At $z \sim 2$ cold streams of gas can still bring material deeply into the haloes, however, most of this gas may be heated before it is accreted to the halo centre (Kereš et al. 2005; Ocvirk et al. 2008). Subsequent work (Kereš et al. 2009) using different hydrodynamic codes found that only a relatively small fraction (typically ∼10–20 per cent of the total halo infall at $z \sim 2$; see Faucher-Giguère, Kereš & Ma 2011) survives all the way to the central galaxy. Cooling of the hot halo in these simulations was not efficient, so this small fraction of surviving cold gas was found to dominate the gas supply to the halo centre. Using another technique, Dekel et al. (2009b) suggested that at $z \sim 2$–3 rapid infall continues unimpeded via narrow filaments all the way to the halo centre even for massive haloes.

Recent simulations using the adaptive mesh refinement and the moving mesh code AREPO [which resolves some numerical inaccuracies previous works using the 'classical smoothed particle hydrodynamics (SPH)' formulation of GADGET; see Springel 2010] find that (absent galactic outflows) the infalling gas is indeed filamentary within the virial radius but may be heated before accretion on to the galaxy (Nelson et al. 2013). In these runs, at $z \sim 2$ a large fraction of gas in a $\sim 10^{12}\,\mathrm{M}_{\odot}$ halo flows as cool gas down to $\sim 0.3\,R_{\rm vir}$; the infalling gas then shock heats, but remains in a coherent structure before it cools again rapidly close to the galaxy (see Kereš et al. 2012; Nelson et al. 2013). However, the gas heating removes some kinetic energy of the infall and forms structures whose coherence lengths exceed the size of the galactic disc (∼10 kpc). Further complexity comes from the halo mass dependence; in lower mass haloes the width of filaments is typically large compared to the galaxy (even when filaments are cold). Thus, the simplest picture of narrow streams of cold gas impacting the galactic disc should only be considered approximate (see discussions in Katz et al. 2003; Kereš et al. 2009; Nelson et al. 2013).

In any case, the consequences of narrow filamentary inflows – assuming they exist – are controversial. For example, it is well known that in a gaseous disc where cooling is efficient, turbulent velocity dispersions should dissipate in a crossing time, so something must continuously maintain the turbulence in galaxies. Although this is often attributed to a combination of stellar feedback and local gravitational instabilities, some authors have argued that the observed turbulent velocity dispersions – especially in high-redshift galaxies [when the galaxies are highly gas rich, as distinct from systems like the Milky Way (MW)] – may be driven in part by the accretion energy (for discussion of this possibility see e.g. Elmegreen & Burkert 2010; Klessen & Hennebelle 2010; Krumholz & Burkert 2010; Cacciato, Dekel & Genel 2012). By extension (if the turbulence can be both driven and efficiently isotropized) this could argue for turbulence driving gas disc thicknesses/scale-heights. In some versions of this argument, maintaining the large-scale turbulence would in turn be sufficient to explain the low star formation (SF) efficiencies of galaxies (i.e. the Kennicutt 1998 relation). Others have argued that the flows directly trigger or enhance secular instabilities in sufficiently gas-rich discs, driving bulge formation (though this may depend on the flow structure, as we discuss in Section 4; see Dekel et al. 2009b; Elmegreen & Burkert 2010).[1]

If it were true that accretion *on to* the galaxy drives turbulence in an *instantaneous* sense, this would imply a radical departure from one of the fundamental assumptions in most analytic or semi-analytic galaxy formation models (indeed including many of the models discussed above). In such models, accretion is the 'fuel supply' which determines the gas mass, angular momentum content, radius etc. of the galaxy disc; these properties in turn determine things like the star formation rate (SFR) and local stability properties, hence ultimately the disc structure and feedback properties. But the inflowing gas, excluding discrete merger events, does not *directly* alter the structural properties of the disc. If the inflow powers the turbulence in the disc, for otherwise *identical* properties in that disc, then the instantaneous properties of the 'accretion flow' will significantly change the gas velocity dispersions within the disc, and hence all the disc properties that depend on the velocity dispersion (e.g. the SFR and stability).

It is critical to assess this claim in numerical simulations, which can simultaneously follow the relevant physics: inflow, gas cooling, SF, stellar feedback and the formation of interstellar medium (ISM) phase structure. Such simulations can follow the complex, non-linear dynamics of turbulence, torques and energy and angular momentum exchange in gas+stellar+dark matter disc galaxies. However, in traditional cosmological simulations – which can self-consistently follow the formation of inflows and their properties – one cannot simply 'remove' the accretion flows, nor vary their properties systematically while keeping the galaxy properties fixed. In other words, cosmological simulations are not controlled experiments as far as accretion flows are concerned.

In addition, achieving the resolution needed to resolve the internal structural properties of the gas disc (resolving the vertical turbulent cascade, for example; see Federrath et al. 2011) is very challenging in a cosmological simulation, with simulation volumes measured in tens of megaparsecs or larger. Even in smaller volume 'zoom-in' simulation, the time-scales which must be simulated (a Hubble time) severely limits the attainable force resolution. Finally, it is well known that the gas properties are strongly affected by feedback from massive stars, so including explicit models for these feedback properties is critical.

In this paper, we therefore use a suite of high-resolution hydrodynamic simulations of isolated disc galaxies (with properties chosen to match observations) and explicit stellar feedback models, including various simplified 'cold flow' models of infalling gas, to investigate these questions. In order to study the influence of infalling gas on the gas dynamics in galaxies, we will consider the most optimistic assumptions (ignoring some of the subtleties above). We will assume that narrow filaments of cool gas do manage to survive

[1] We should caution that 'accretion-driven turbulence' can have many different meanings, and is used differently in some of these examples. Much of the focus on these papers is on the role of accretion *through* a galactic disc, powered itself via gravitational instabilities, and its relation to turbulence, or accretion *within* the disc on to individual molecular clouds. That is not the focus of this paper. Rather, we investigate the very specific question of the role of accretion *on to* the galaxy.

and plunge into the disc of the galaxy. Furthermore, we assume that infall rates from cold mode accretion on to galaxies represent the full infall rate on to haloes (clearly an upper limit). Our purpose is to see if such filamentary accretion can drive high velocity dispersion and scale-heights of galaxies, and to assess the relative importance of this process when compared to star-formation-driven feedback.

2 THE SIMULATIONS

The simulation method we use is described in detail in Hopkins, Quataert & Murray (2011, section 2 and tables 1–3; hereafter Paper I) and Hopkins, Quataert & Murray (2012a, section 2; hereafter Paper II). We briefly summarize the most important properties here. The simulations were performed with a heavily modified version of the parallel Tree-SPH code GADGET-3 (Springel 2005), in a fully conservative formulation (Springel & Hernquist 2002) which is also density independent (the 'pressure-entropy' formulation of SPH) in a manner that allows contact discontinuities and improved fluid mixing (Hopkins 2013). The artificial viscosity, adaptive time-stepping and smoothing kernel are updated as described therein.[2] They include stars, dark matter and gas, with cooling, shocks, SF and stellar feedback.

In our simulations gas follows an atomic cooling curve with additional fine-structure cooling to 10 K, allowing for the photoionizing background computed in Faucher-Giguère et al. (2008) and gas self-shielding. Metal-line cooling is followed species-by-species for 11 tracked species as in Wiersma, Schaye & Smith (2009a) and Wiersma et al. (2009b). The enrichment for each species is followed with the appropriate time dependence with independent yields directly attached to mass and energy return from individual feedback sources described below. SF is allowed only in dense, molecular, self-gravitating regions above $n > 1000\,\mathrm{cm}^{-3}$. We follow Krumholz & Gnedin (2011) to calculate the molecular fraction $f_{\mathrm{H_2}}$ in dense gas as a function of local column density and metallicity, and allow SF only from molecular gas. We also restrict SF to gas which is locally self-gravitating, i.e. has $\alpha \equiv \delta v^2\,\delta r / G\, m_{\mathrm{gas}}(<\delta r) < 1$ on the smallest available scale (δr being our force softening or smoothing length). This forms stars at a rate $\dot{\rho}_* = \rho_{\mathrm{mol}}/t_{\mathrm{ff}}$ (i.e. 100 per cent efficiency per free-fall time); however, the galaxy-wide efficiency is generally much lower because of feedback. In Paper I and Paper II we show the galaxy structure and SFR are basically independent of the small-scale SF law, density threshold (provided it is high) and treatment of molecular chemistry, because the SF (and hence galactic structure) is feedback regulated.

Stellar feedback is included from a variety of mechanisms.

(1) *Local momentum flux from radiation pressure, supernovae and stellar winds*. Gas within a giant molecular cloud (GMC; identified with an on-the-fly friends-of-friends algorithm) receives a direct momentum flux from the stars in that cluster/clump. The momentum flux is $\dot{P} = \dot{P}_{\mathrm{SNe}} + \dot{P}_{\mathrm{w}} + \dot{P}_{\mathrm{rad}}$, where the separate terms represent the direct momentum flux of SNe ejecta, stellar winds and radiation pressure. The first two are directly tabulated for a single stellar population (SSP) as a function of age and metallicity Z and the flux is directed away from the stellar centre. Because this is interior to clouds, the systems are always optically thick, so the latter is approximately $\dot{P}_{\mathrm{rad}} \approx (1 + \tau_{\mathrm{IR}})\, L_{\mathrm{incident}}/c$, where $1 + \tau_{\mathrm{IR}} = 1 + \Sigma_{\mathrm{gas}}\, \kappa_{\mathrm{IR}}$ accounts for the absorption of the initial ultraviolet (UV)/optical flux and multiple scatterings of the infrared (IR) flux if the region is optically thick in the IR (with Σ_{gas} calculated for each particle).

(2) *Supernova shock heating*. Gas shocked by supernovae can be heated to high temperatures. We tabulate the Type I and Type II SNe rates from Mannucci, Della Valle & Panagia (2006) and STARBURST99, respectively, as a function of age and metallicity for all star particles and stochastically determine at each time-step if a SNe occurs. If so, the appropriate mechanical luminosity is injected as thermal energy in the gas within the nearest ∼32 neighbours of the star particle.

(3) *Gas recycling and shock heating in stellar winds*. Gas mass is returned to the ISM from stellar evolution, at a rate tabulated from SNe and stellar mass loss (integrated fraction ≈0.3). The SNe heating is described above. Similarly, stellar winds are assumed to shock locally and inject the appropriate tabulated mechanical luminosity $L(t, Z)$ as a function of age and metallicity into the gas within a smoothing length.

(4) *Photoionization and photoelectric heating*. We also tabulate the rate of production of ionizing photons for each star particle; moving radially outwards from the star, we then ionize each neutral gas particle (using its density and state to determine the necessary photon number) until the photon budget is exhausted. Ionized gas is maintained at a minimum $\sim 10^4$ K until it falls outside an H II region. Photoelectric heating is followed in a similar manner using the heating rates from Wolfire et al. (1995).

(5) *Long-range radiation pressure*. Photons which escape the local GMC [not accounted for in (1)] can be absorbed at larger radii. Knowing the intrinsic spectral energy distribution (SED) of each star particle, we attenuate integrating the local gas density and gradients to convergence. The resulting 'escaped' SED gives a flux that propagates to large distances, and can be treated in the same manner as the gravity tree to give the local net incident flux on a gas particle. The local absorption is then calculated integrating over a frequency-dependent opacity that scales with metallicity, and the radiation pressure force is imparted.

Details and numerical tests of these models are discussed in Paper II. All energy, mass and momentum-injection rates are taken as-is from the stellar population models in STARBURST99, assuming a Kroupa (2002) initial mass function (IMF), without any free parameters. Subtle variations in the implementation do not make significant differences to our conclusions.

We implement the model in three distinct initial disc models spanning a range of galaxy types. Each has a bulge, stellar and gaseous disc, halo and central black hole (BH; although to isolate the role of stellar feedback, models for BH growth and feedback are disabled). At our standard resolution, each model has ~ 0.3–1×10^8 total particles, giving particle masses of 500–1000 $\mathrm{M}_{\odot}$ and 1–5 pc smoothing lengths, and are run for a few orbital times each. In Paper II, a couple ultrahigh resolution runs for convergence tests employ $\sim 10^9$ particles with sub-pc resolution. The disc models include the following.

[2] There has been considerable discussion in the literature regarding subtle numerical effects on inflow properties and the treatment of subsonic multiphase flows (see references in Section 1). Our method is specifically designed to better treat this regime. However, we have also re-run our HiZ model with feedback with the alternative 'classical SPH' formulation in Springel & Hernquist (2002) and that in Abel (2011), as well as varied artificial viscosity and resolution, and find our major conclusions are robust. We believe this is because we focus on the galactic disc, not flow formation and interaction with the hot halo. In the former regime, the shocks and relevant turbulent cascade are highly supersonic and external forcing (from gravity and feedback) is important; this is the regime where the various numerical approaches agree well (see Kitsionas et al. 2009; Price & Federrath 2010; Bauer & Springel 2012).

(1) Small Magellanic Cloud (SMC): an SMC-like dwarf, with baryonic mass $M_{\rm bar} = 8.9 \times 10^8\,{\rm M_\odot}$ (gas $m_{\rm g} = 7.5 \times 10^8\,{\rm M_\odot}$, bulge $M_{\rm b} = 1.3 \times 10^8\,{\rm M_\odot}$, the remainder in a stellar disc $m_{\rm d}$) and halo mass $M_{\rm halo} = 2 \times 10^{10}\,{\rm M_\odot}$. The gas (stellar) scale length is $h_{\rm g} = 2.1$ kpc ($h_{\rm d} = 0.7$).

(2) MW: a MW-like galaxy, with halo $M_{\rm halo} = 1.5 \times 10^{12}$, and baryonic $(M_{\rm bar}, m_{\rm b}, m_{\rm d}, m_{\rm g}) = (7.1, 1.5, 4.7, 0.9) \times 10^{10}\,{\rm M_\odot}$ with scale-lengths $(h_{\rm d}, h_{\rm g}) = (3.0, 6.0)$ kpc.

(3) HiZ: a high-redshift massive starburst disc, typical of massive star-forming galaxies at $z \sim 2$–4; $M_{\rm halo} = 1.4 \times 10^{12}\,{\rm M_\odot}$ (scaled for $z = 2$ haloes), and baryonic $(M_{\rm bar}, m_{\rm b}, m_{\rm d}, m_{\rm g}) = (17, 7, 3, 7) \times 10^{10}\,{\rm M_\odot}$ with scale-lengths $(h_{\rm d}, h_{\rm g}) = (1.6, 3.2)$ kpc.

We consider each model with and without a ‘cold flow’. Motivated by the cosmological simulations cited in Section 1, we initialize the flow as a narrow cone of gas with opening angle ϕ, infalling at the free-fall velocity (from infinity). We typically assign the flow a small initial turbulent dispersion, ≈20 per cent of the mean velocity, and a subvirial initial $T \approx 10^5$ K; we have varied these parameters, and found little effect on the results. The flow is initialized so the mean $\dot{M}$ through all conical annuli is constant, towards an impact parameter at a radius b in the disc, with a relative inclination θ. We initialize the flow with sufficient mass and extent to ensure it is maintained for the duration of the simulation. Because such flows are believed to be the ultimate source of the disc gas, our default choice for b is $R_{\rm e,\,gas}$ (the effective radius of the gas disc), with a prograde orientation (i.e. with the flow having the same sign of angular momentum as the disc), with a narrow (20°) opening angle, and $\dot{M}$ approximately equal to the maximal halo baryon accretion rate (halo growth rate, for a mean halo of the given mass and redshift, times the universal baryon fraction; $=0.15, 10.0, 200\,{\rm M_\odot\,yr^{-1}}$ for the SMC, MW, HiZ models, respectively). As explained in Section 1, these rates are purposely set to be maximally optimistic; typical (median) haloes will have lower accretion rates, and not all of the infall will survive all the way to the galaxy as part of a coherent structure.

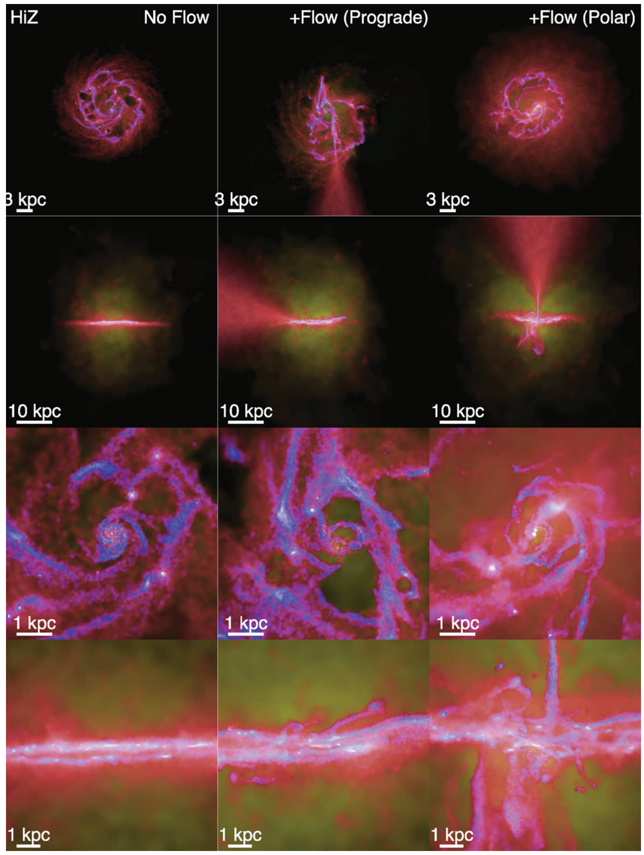

Figure 1. Morphology of the gas in simulations of a massive $z \sim 2$–4 starburst disc with $\dot{M}_* \sim 200\,{\rm M_\odot\,yr^{-1}}$. Images are shown at ∼3.5 orbital times when the disc is in a feedback-regulated steady-state. We show face-on (upper) and edge-on (lower) projections, at large (halo) scales and small (star-forming disc) scales, as labelled. All models shown include stellar feedback. We compare a case with no inflow (left), with our ‘default’ mock cold flow (inflow rate $\dot{M} \sim 200\,{\rm M_\odot\,yr^{-1}}$, aligned with disc rotation; *centre*), and with a similar flow oriented perpendicular to the disc rotation (right). The images are at extremely high resolution/depth. Brightness encodes projected gas density (logarithmically scaled with ≈6 dex stretch); colour encodes temperature with blue/white being $T \lesssim 1000$ K molecular gas, pink $\sim 10^4$–10^5 K warm ionized gas, and yellow $\gtrsim 10^6$ K hot gas. The qualitative morphology, with massive kpc-scale molecular complexes, is similar in each case. Warps and out-of-plane streams make the disc appear thicker with flows. Out-flowing winds are seen in all simulations, but are slightly enhanced when inflows are present.

3 RESULTS

Fig. 1 compares the gas morphologies of our ‘default’ HiZ runs with and without ‘flows’ present. The results are broadly similar within the effective radii of the gaseous discs. Inflows clearly lead to more gas distributed outside the star-forming disc, both in the form of streams and filaments falling in, as well as in additional wind material. Over several orbits the inflows modify the outer disc, essentially by replacing it with material on new orbits (determined by the flow parameters). The visual differences are less pronounced in the MW and SMC models.

In Figs 2 and 3, we examine the effects on galaxy properties. Fig. 2 examines the ‘default’ model in each case, with and without flows present, and with and without feedback. In Fig. 3, we vary the properties of the flow, in our HiZ model with feedback present. We have varied the properties in similar fashion in the MW and SMC runs, but find smaller variation in those cases. This should not be surprising; the gaseous discs are much less strongly self-gravitating in the MW and SMC runs (so less sensitive to external perturbations), and with a much higher inflow rate and SFR the gas ‘replenishment’ time in the HiZ case is nearly an order of magnitude faster than in the MW and SMC cases, hence the HiZ disc is ‘more dominated’ by inflow and that inflow is much more energetic.

In all cases, as shown in Paper I and Paper II, without feedback, the gas radiates away its support and locally collapses into dense clumps, globally turning most of its mass into stars in a single dynamical time. The SFRs correspond to $\dot{M}_* \sim M_{\rm gas}/t_{\rm dyn}$, an order-of-magnitude or more in excess of the observed Kennicutt relation. The absolute SFRs decline at later times only because the gas is exhausted, but always exceed the rate given by the Kennicutt relation. The presence of an accretion flow makes no difference to the SFR relative to Kennicutt; it simply provides more fuel to sustain the runaway SFR longer. With feedback present, the SFRs self-regulate at a level in good agreement with the observed Kennicutt relation (see Paper I). When feedback is included, the inflow has no effect on the SFR, scaled to Kennicutt; at late times the flows maintain the disc gas densities, slowing the decline in SFR.

We next examine the internal gas disc properties. The three-dimensional gas velocity dispersion is plotted (as a function of radius) in the third row of Fig. 2. We take the average over all snapshots after the first disc orbital period, when the system is in

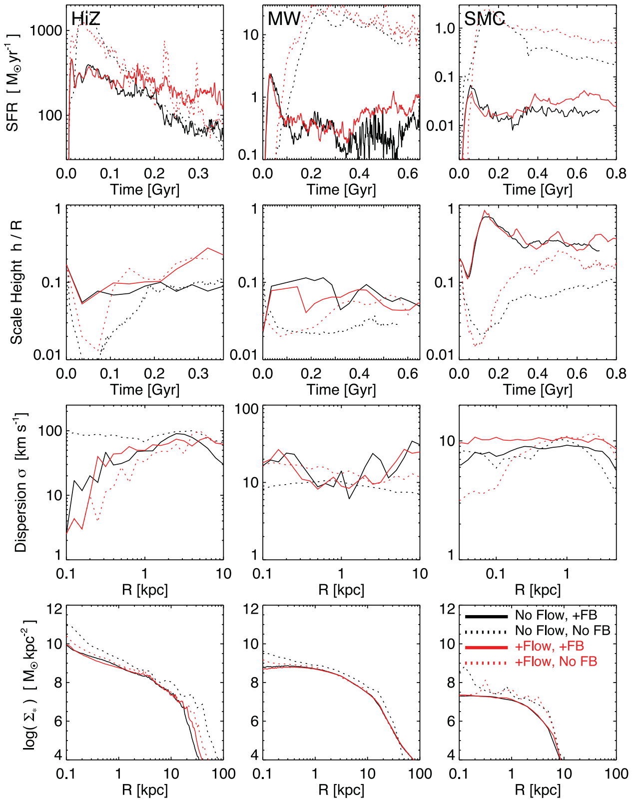

Figure 2. Effects of cold 'accretion flows' on galaxy properties. Each column shows a different galaxy type (Section 2). For each, we show models with/without a flow (using the 'default' flow parameters) and with/without stellar feedback. Top: SFR versus time. With feedback, models self-regulate near observed SFRs; late-time SFRs with flows are higher because gas is replenished, but both lie on the same Kennicutt–Schmidt relation. Without feedback, both experience runaway local collapse/SF. Second: vertical disc scale height h/R. Feedback maintains higher values by powering turbulence and isotropizing in-plane gas motions. The flows may help isotropize the gas (especially without feedback) and boost h/R by depositing low-binding energy material above/below the disc. Third: gas velocity dispersion versus radius (time-averaged). All models maintain $Q \sim 1$, giving similar σ, independent of feedback and flows.[3] Bottom: final stellar mass profile (at the end of the simulation). Disc instabilities drive some bulge growth in each case, sensitive to feedback, but without a clear dependence on flows.

equilibrium. In Paper II we showed that discs always self-regulate at $Q \sim 1$, so the dispersion σ is similar regardless of the presence/absence or details of feedback. Without feedback, there are some subtle differences: flows do increase the dispersion in the SMC and MW cases by a small amount, but actually have the opposite effect in the HiZ case.[3] With feedback present, these effects are washed out, and we see no statistically significant or meaningful difference with or without inflows.

The second panel of Fig. 2 shows the disc scale height h/R, which is related specifically to the vertical disc dispersion σ_z. In Paper II, we showed that h is different in cases with or without feedback. Simulations lacking feedback and inflow maintain σ via global

[3] The dispersion in the HiZ case with no feedback or inflow is very large especially at <1 kpc. This is because the extremely rapid SF (in the absence of feedback), without continuous inflow, rapidly exhausts the central gas, and the dispersion is dominated by hot (volume-filling) gas and the occasional dense gas clump inspiraling near the circular velocity.

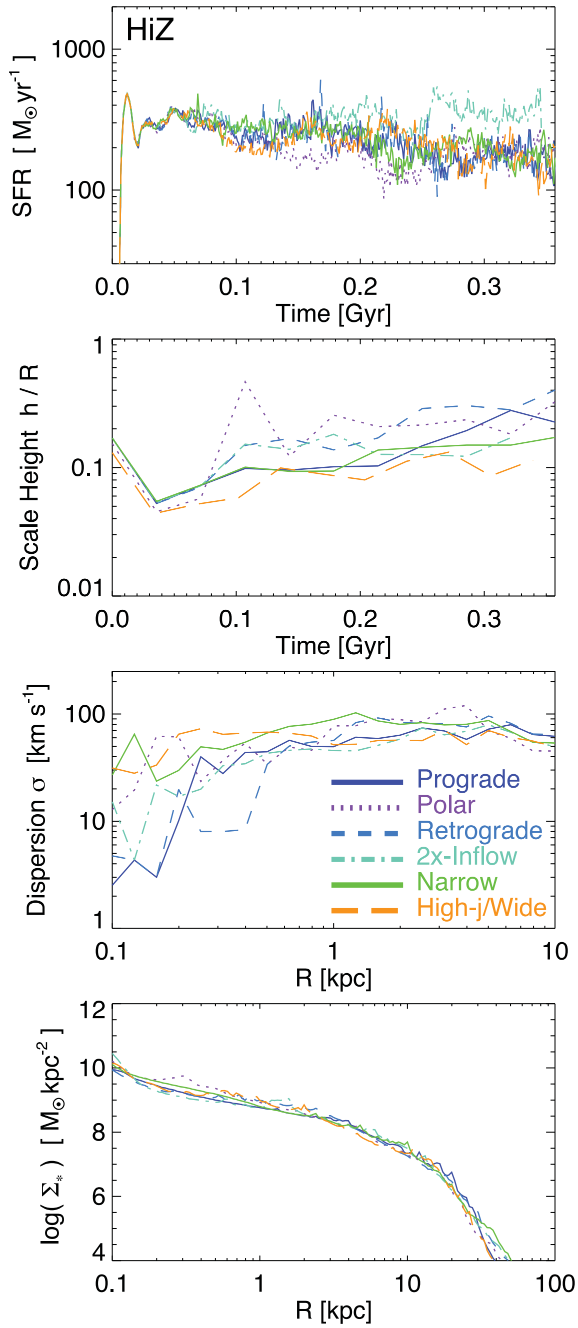

Figure 3. Galaxy properties as Fig. 2. Here, we focus on the HiZ model (which has a more extreme inflow than the SMC or MW model) but vary the inflow properties. All models include 'cold flows'. We compare our default cold flow model (prograde – i.e. aligned with the disc, with $\dot{M}_{\rm gas} = 200\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ and impact parameter $b = R_{\rm e}$) to models with different relative flow/disc orientations (a model where the flow is polar, i.e. perpendicular to the disc rotation, and a model where the flow is retrograde, i.e. directly oppose the disc rotation), with different flow rates (prograde, $400\,{\rm M}_{\odot}\,{\rm yr}^{-1}$), and with different impact parameters ('narrow' with $b = 0.5\,R_{\rm e}$ and cross-section smaller by 1/2, and 'high-*j*/wide' with $b = 2\,R_{\rm e}$ and cross-section larger by 2). There is very little dependence of the disc properties on these choices except, perhaps, just at the location where the flow meets the disc. Flows with higher angular momentum (impact parameter $>R_{\rm e}$) are similar but appear to have weaker effects on scale-height.

gravitational instabilities and 'one-way' collapse, as e.g. a collapsing clump increases in σ as it collapses to a resolution-limited small radius. In a disc this gravitationally induced velocity dispersion is preferentially in-plane and leads to large velocity anisotropy, and hence smaller h/R than seen in observations. In the simulations including inflows, the difference between feedback and no-feedback runs is reduced somewhat, i.e. the red dotted line recovers to the solid red line within a couple orbits (though in the lower mass SMC case, feedback effects on the dispersion are larger so there is still a difference between the results). Visually (Fig. 1), the discs appear 'thicker' with inflows because the streams directly contribute some gas in out-of-plane orbits, and misalignment of disc and stream leads over a few orbits to warps; the flows may also help isotropize the gas dispersions, boosting h/R over what it would be without inflows. Comparing to the run lacking *both* feedback and inflows, the difference is significant. However, these inflow-driven effects do not much change h/R compared to the no-inflow run with feedback. And the effect on h/R becomes weaker if we systematically increase the impact parameter (and angular momentum) of the inflow; since the dispersions are similar, this appears to be related to the ability of the disc to relax to equilibrium.

We also show the stellar mass profiles at the conclusion of each simulation, after $\sim$0.5 Gyr of evolution. In Hopkins et al. (2012c), we discuss how feedback alters the efficiency of secular evolution, particularly for the HiZ model, comparing the mass profiles with and without feedback. Without feedback, gas experiences runaway local collapse into dense 'nuggets' which then have no choice but to sink to the galaxy centre. This leads to artificially large/rapid bulge formation. We see here the large difference in the bulge formed in the HiZ model with and without feedback (at small radii in the bottom row, the black dotted line lies well above the other lines). Also, without feedback, the outer disc evolves outward as a result of absorbing the angular momentum from these sinking clumps. It has been argued that inflows lead to rapid bulge build up (Dekel, Sari & Ceverino 2009a). We do not see this in our simulations – in fact if anything we find that inflow, in the absence of feedback, leads to *smaller* bulges than in simulations lacking both feedback and inflows. If feedback is included, the presence or absence of an inflow has little or no effect on bulge size.

4 DISCUSSION

We consider idealized simulations of isolated disc galaxies with and without large 'cold streams', where the cosmological inflows are represented as simplified streams of cold gas free-falling on to the galaxy. This is a crude approximation to the full cosmological case, but unlike in cosmological simulations, our simulations allow us to add, remove or modify flows while maintaining otherwise identical galaxy properties, i.e. they allow for controlled numerical experiments. The smaller simulation box sizes used also allow us to reach pc-scale and $\sim$100 yr resolution and include explicit, spatial and time-resolved models for stellar feedback from SNe (Types I and II), stellar winds [O-star and asymptotic giant branch (AGB)], photoionization and radiation pressure.

We show that in an *instantaneous* sense – i.e. for otherwise fixed galaxy properties – the presence or absence of an inflow has only a small effect on the galaxy. The SFR in either case is regulated by feedback: as shown in Paper II, with explicit feedback, gas cools and collapses until enough young stars are formed to inject sufficient momentum and regulate against further collapse. As a result, the SFR is set by feedback entirely independent of e.g. the small-scale SF law or the presence of cold stream accretion. In other words, the flows have no direct effect on the SFR. They do affect the SFR over long times, not because they affect the dynamics of the ISM, but because they affect the amount of gas in the disc. Without feedback, local collapse runs away in a dynamical time, giving $\dot{M}_* \sim M_{\rm gas}/t_{\rm dyn}$ ($\sim$50 times larger than observed). This is not altered with flows present. In the absence of feedback, cold streams are unable to prevent runaway local collapse or 'slow down' SF via turbulence. Indeed, as shown in Hopkins (2012), any mechanism that drives turbulence only on large scales, but does not breakup locally self-gravitating regions, is insufficient to stave off runaway local collapse.

We also find that the velocity dispersions are weakly sensitive to the flow properties. This is consistent with the result in Paper II that a combination of feedback and gravitational instability always drives the velocity dispersion to values such that the Toomre $Q \sim 1$ (with any 'excess energy' efficiently radiated), such that the velocity dispersion does not change upon adding or removing individual feedback coupling or turbulent driving mechanisms. It follows that the stability properties of the galaxies are not significantly altered by the presence of inflows.

Nor do inflows appear to strongly alter the rate of secular evolution or angular momentum transfer in the disc. Disc instabilities, which are present in all the simulations shown here, are primarily sensitive to local properties. The inflow we model is smooth and extended, and so does not introduce a strong resonant response (see e.g. D'Onghia et al. 2010), unlike the case in a galaxy merger.

Feedback efficiently powers turbulence and isotropizes the dispersions, so with feedback on we see little difference in the disc scale-height when in inflow is turned on or off. However, in runs without feedback, the velocity dispersion is largely in-plane in the no-flow case, so adding an inflow 'stirs' the disc and boosts its thickness significantly. We note, though, that these no-feedback, inflow-stirred discs are still thinner than discs with feedback present. Flows do make the discs appear thicker, by contributing some out-of-plane star-forming gas directly, and, over time, generating warps and misalignments. This is not a consequence of the flow dynamically disturbing, stirring or driving the disc, but rather of the disc material (coming from the flow) having a different angular momentum distribution (with misaligned material) in our idealized, isolated galaxy models. With sufficient time (if the flow is stable), the situation will likely relax into a new disc aligned with the flow, though situations where the flow is constantly changing in orientation (if they occur in cosmological simulations) would be particularly interesting to study in the future.

If we examine the location where inflow meets disc, we see a mix of behaviours. Some diffuse material undergoes a series of radiative shocks, but the relative velocities in each are sufficiently small that this places material near the peak of the cooling curve and so the energy is efficiently dissipated. More dense streams and clumps fall in ballistically, and can penetrate the disc, forming the misaligned streams discussed above, which are gradually torqued into equilibrium orbits.

We also note that the feedback-driven outflows or winds discussed in detail in Hopkins, Quataert & Murray (2012b) are not strongly altered with cold flows present, although overall the outflow mass-loading rates ($\dot{M}_{\rm wind}/\dot{M}_*$) are enhanced by factors of $\sim$1.5–2 (reflected in the extended outflows in Fig. 1), because the inflow includes material which is marginally bound. This marginally bound inflowing material can be accelerated by radiation pressure and hot gas ram pressure at large radii, i.e. it is accelerated off of the surface of the stream.

The 'cold flow' models here represent extreme cosmological situations, in that they have mass inflow rates equal to the entire baryonic halo accretion rate and assume 100 per cent of the infall is in 'cold mode'. They are infalling at the free-fall velocity, reaching the galaxy, and there is (by design) no hot halo to resist their infall or strip the streams. They also have impact parameters very close to the disc effective radii. More realistic situations in cosmological simulations may produce weaker effects than those here. This is especially the case in lower redshift or more massive haloes like the MW, where much of the gas is probably shocked to virial temperatures with long cooling times. Furthermore, in massive haloes, even at $z \sim 2$ gas delivered from minor mergers might be an important channel of gas supply (Kereš et al. 2009). Moreover, recent simulations using different numerical methods have questions some early conclusions about the dynamics of infalling gas, arguing for example that the streams may be more smooth and diffuse, and more efficiently stripped/mixed by halo gas as they approach the disc, than some earlier calculations (mostly using 'classical SPH') had estimated (Bauer & Springel 2012; Kereš et al. 2012; Sijacki et al. 2012; Vogelsberger et al. 2012).

In many ways, our results confirm the 'conventional wisdom' in this subject. However, one way in which accretion could introduce stronger perturbations than what we consider here is if it were very 'clumpy', with a large fraction of the incoming mass in units with sizeable masses relative to the disc (see particularly Dekel et al. 2009b). Hopkins et al. (2008) discuss the resonant response to radially infalling clumps/galaxies, and D'Onghia et al. (2010) consider non-merging passages; both suggest that significant effects could occur if the clumps have masses $\gtrsim$10 per cent of the disc, effectively acting as minor mergers. And indeed there may be a large number of such clumps and/or mergers 'carried in' with the flows (see e.g. Kereš et al. 2005, 2009; Dekel et al. 2009b, although also see the numerical caveats above). The response of discs to minor mergers and harassment, however, is well developed and studied in a number of other contexts, and is outside the scope of our investigation here. But to the extent that this is important, our results suggest it may be separable into a merger-like contribution from individual massive clumps falling in, and a weaker contribution from the 'smooth accretion flow'.

We are of course *not* arguing that 'cold' accretion is unimportant for galaxy formation. None of our arguments change whether gas enters the halo without undergoing virial shocks or with cooling times short compared to dynamical times and so reaches the galaxy rapidly. This gas is the supply for SF on cosmological time-scales; therefore, it (with the effects of subsequent feedback) determines the disc gas mass, stellar mass and angular momentum content of the galaxy, which *in turn* determine the SFR, velocity dispersion and secular stability (see e.g. Brooks et al. 2009; Federrath & Klessen 2012). Both theoretical (Kereš et al. 2005) and observational (e.g. Daddi et al. 2007) arguments indicate that continuous gas accretion is necessary to explain long term SF activity of galaxies. For example, on cosmological time-scales, the 'equilibrium SFR' of galaxies will be set in part by the rate of inflow: the gas consumption rate is $\dot{M}_* + \dot{M}_{\rm wind}$, where $\dot{M}_{\rm wind} \propto \dot{M}_*$ for otherwise similar properties (Paper III). If this falls below the infall $\dot{M}_{\rm acc}$, a gas reservoir inevitably builds up, increasing the SFR until $\dot{M}_{\rm acc} \sim \dot{M}_* + \dot{M}_{\rm wind}$. However, SF (and the generation of outflows) does not directly 'know' about the inflow. Rather, inflows (in competition with SF and outflow) determine the gas supply, which determines the SFR locally needed to prevent runaway local collapse, which determines the actual SFR, which then determines the outflow properties.

In short, we argue that the role of accretion is to *cosmologically* determine the 'initial' global properties of the galaxy, e.g. the gas and angular momentum supply rate. For a given set of those global properties, the local instantaneous properties of the galaxy are set by a combination of local dynamical and feedback processes that operate on much smaller spatial and time-scales.

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